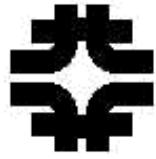


Nb₃Sn High-Field Dipoles for VLHC with Cos-theta Coils

A.V. Zlobin, Fermilab

Outlines:

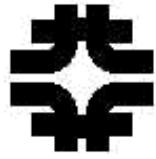
- *Design Parameters and Criteria*
- *Magnet Development Status*
- *Magnet Designs: single/double bore, cold/warm yoke*
- *Design Parameters: field quality, mechanics, quench protection, short sample limit, etc.*
- *Summary*



Design Parameters and Criteria

Preliminary requirements to HFM for VLHC (Snowmass'96):

- nominal field: **B_{nom}=10-12 T**
- field range: **B_{nom} / B_{inj}=50TeV / 3TeV=17 \Rightarrow B_{inj}=0.6-0.7 T**
- good field quality in the operation cycle: **1986 SSC specs**
- sufficient dynamic aperture: **magnet bore 30-50 mm**
- beam screen
- full-scale magnet length: **10-15 m**
- mechanical and thermal stability
- quench protection
- performance reproducibility
- low cost: **small coil & magnet x-sections,
simple & inexpensive technology**



Magnet Development Status

Study of two design types: cos-theta and block (common coil)

Exploration of two fabrication techniques: wind&react and react&wind

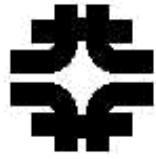
Conceptual study has been completed in FY99 for single bore magnet including

- cross-section optimization
- short sample limit for B_{max}
- field quality
- mechanical analysis
- quench protection
- fabrication technology

Short model R&D program has been started

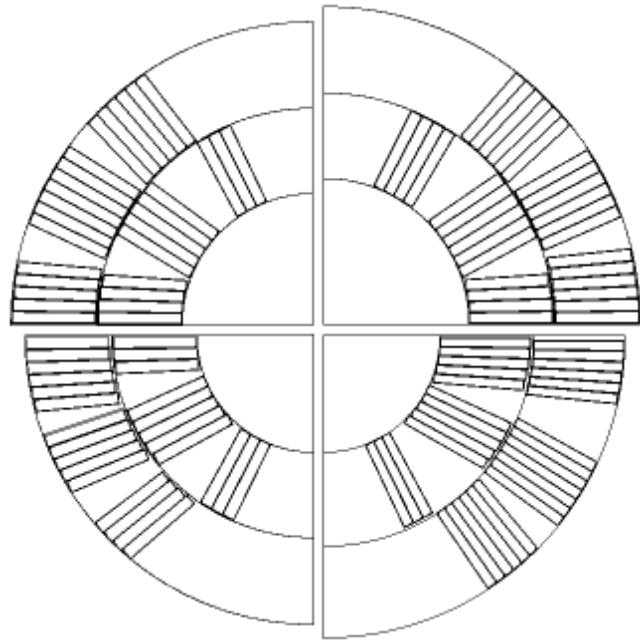
Magnet fabrication and test infrastructure for short Nb₃Sn model magnets is being developed

Conceptual design study of double bore magnets and different magnet design is being continued



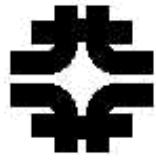
Magnetic Design Study

Basic parameters: 2 layers, cos-theta coil
coil thickness ~30 mm

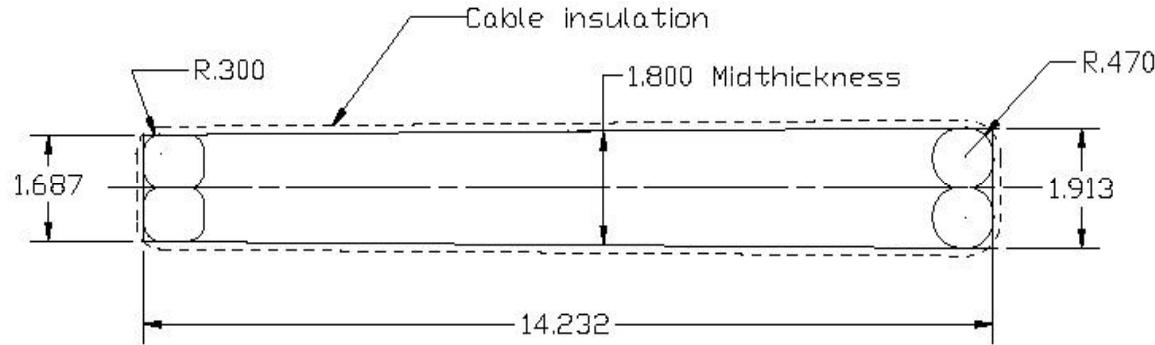


Cross-sections of coils with
bore diameter of 40-50 mm and
strand diameter of 0.81 and 1.0 mm

| Cable | 1.80x14.23mm ² | 1.46x15.4mm ² | | |
|-----------------------------------|---------------------------|--------------------------|------|------|
| Bore diam. (mm) | 50 | 45 | 40 | 40 |
| Turns per dipole | 64 | 60 | 52 | 64 |
| B/ I (T/ kA) | 0.76 | 0.74 | 0.68 | 0.81 |
| B_{ss} (T) | 12.4 | 12.4 | 12.5 | 12.5 |
| Iss (kA) | 16.8 | 16.8 | 18.5 | 15.4 |
| Inom (kA) | 14.5 | 14.9 | 16.2 | 13.5 |
| Energy @11T (kJ/ m) | 289 | 256 | 221 | 230 |
| Inductance (mH/ m) | 2.75 | 2.32 | 1.67 | 2.53 |
| Coil area (cm²) | 33.0 | 30.1 | 26.6 | 28.7 |
| Pole width (mm) | 17.5 | 16.2 | 15.0 | 14.6 |



Cable and Insulation



Strand parameters:

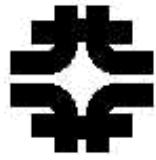
| | |
|----------------------------|----------------------------|
| Superconductor | Nb ₃ Sn |
| Strand diameter | 1.00mm |
| Cu:nonCu | 0.85:1 |
| J _c (12T, 4.2K) | 1.8-2.0 kA/mm ² |
| I _c (12T, 4.2K) | 750-850 A |
| d _{eff} | 100-120 μ m |

Cable parameters:

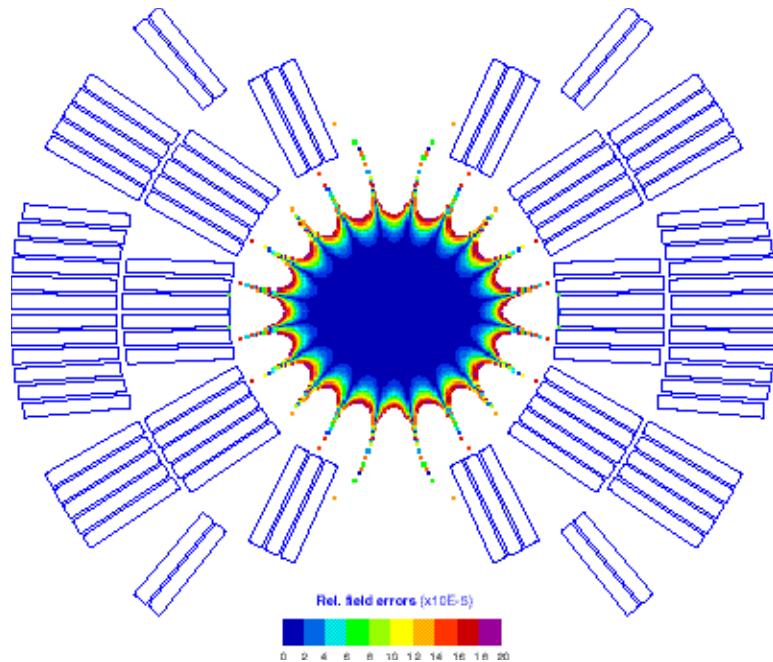
| | |
|----------------------------|-------------------------|
| Number of strands | 28 |
| Cable width | 14.24mm |
| Mean thickness | 1.800mm |
| Packing factor | 0.884 |
| SS core | 0.025*12mm ² |
| I _c degradation | ~5% |
| I _c (12T, 4.2K) | 21-22 kA |

Insulation:

Ceramic tape 2*0.125 mm (50% overlap)

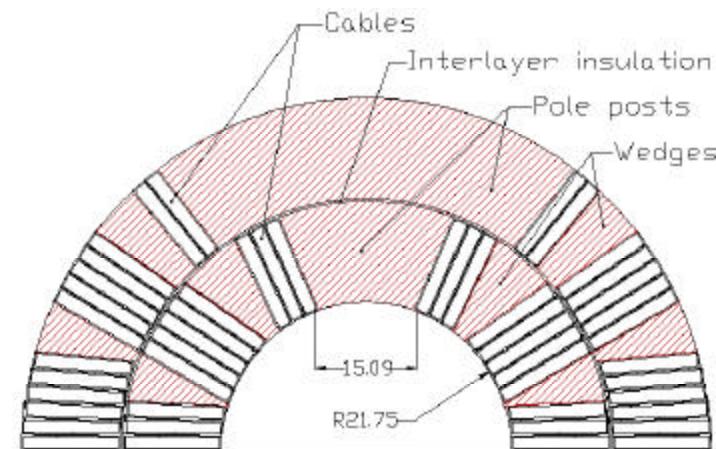


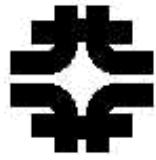
Coil Cross-Section



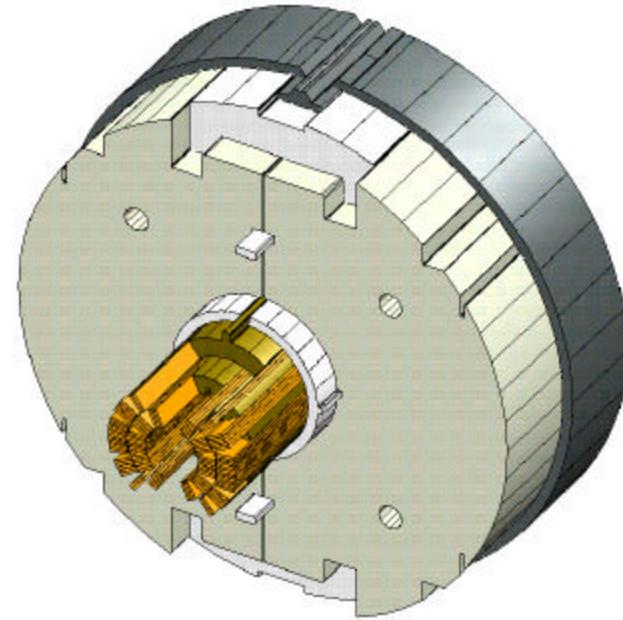
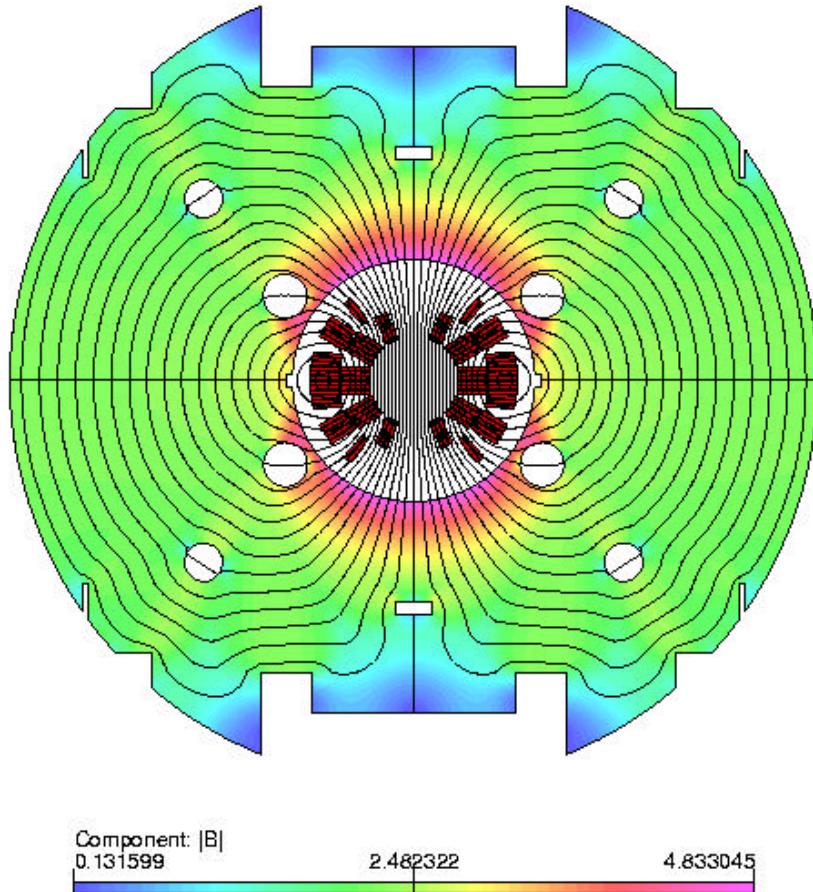
Coil parameters:

- 2 layers cos-theta
- bore diameter 43.5 mm
- 6 blocks (3+3)
- 24 turns (11+13)
- inner pole width: 15.1 mm
- w/o inter-layer splices





Single-Bore Cold-Yoke Design

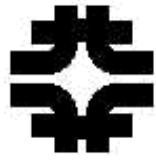


Magnet parameters:

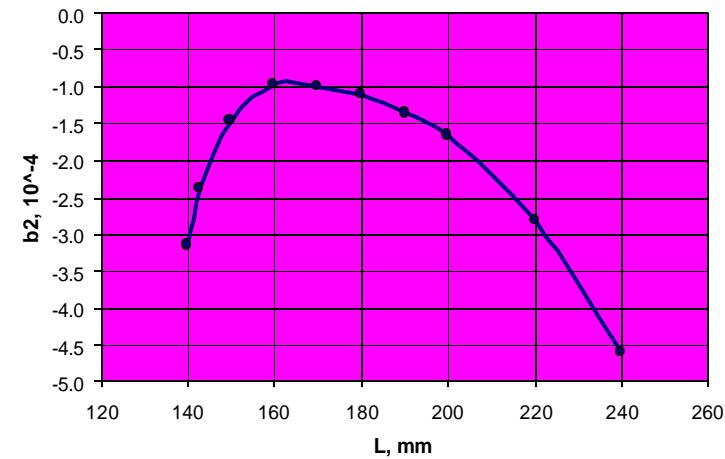
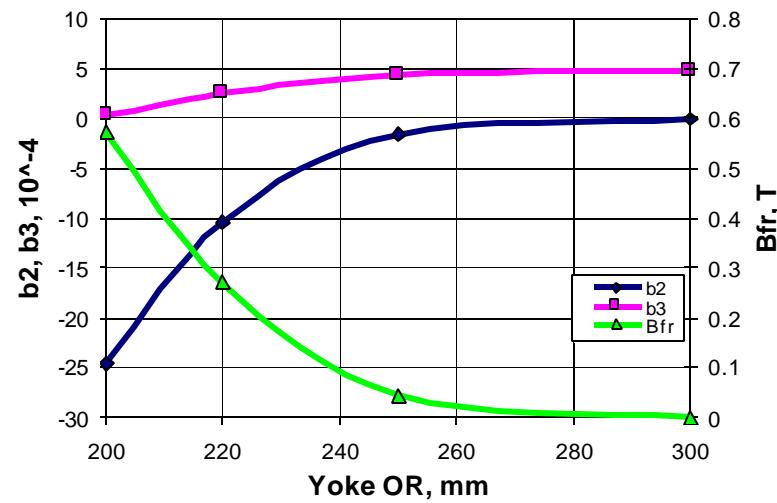
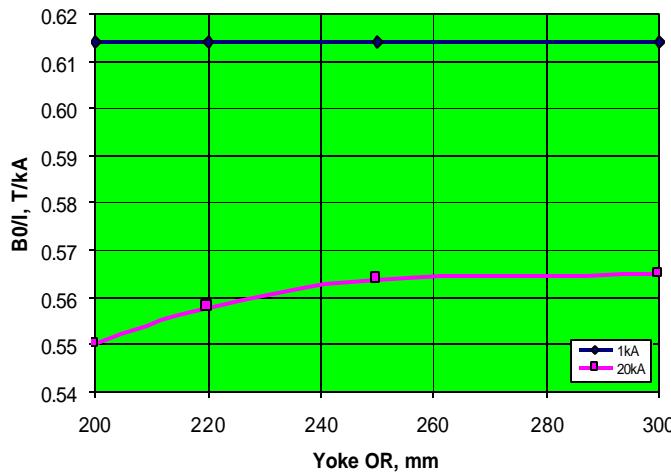
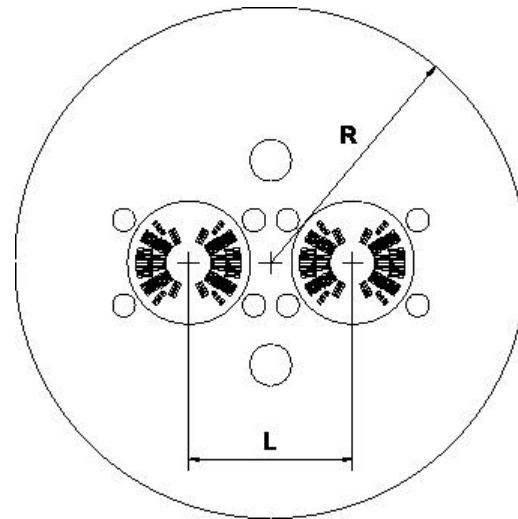
- thin coil-yoke spacers (no collars)
- 2 pieces cold yoke with open vertical gap
- Al clamps and 10 mm thick SS skin
- yoke OD 400-425 mm

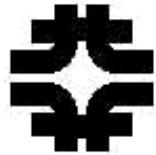
Short models (simplified design)

Single bore magnet

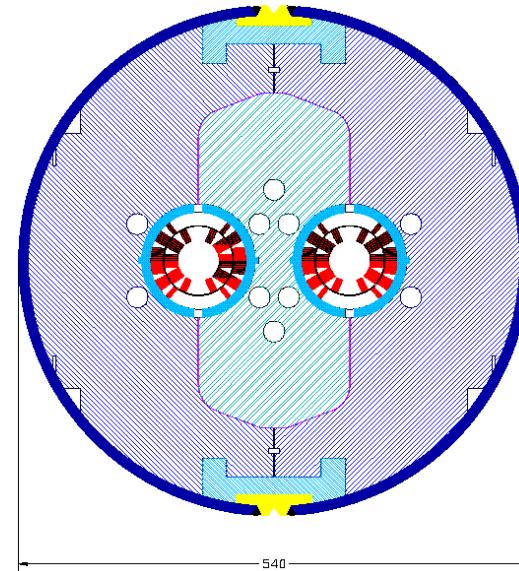
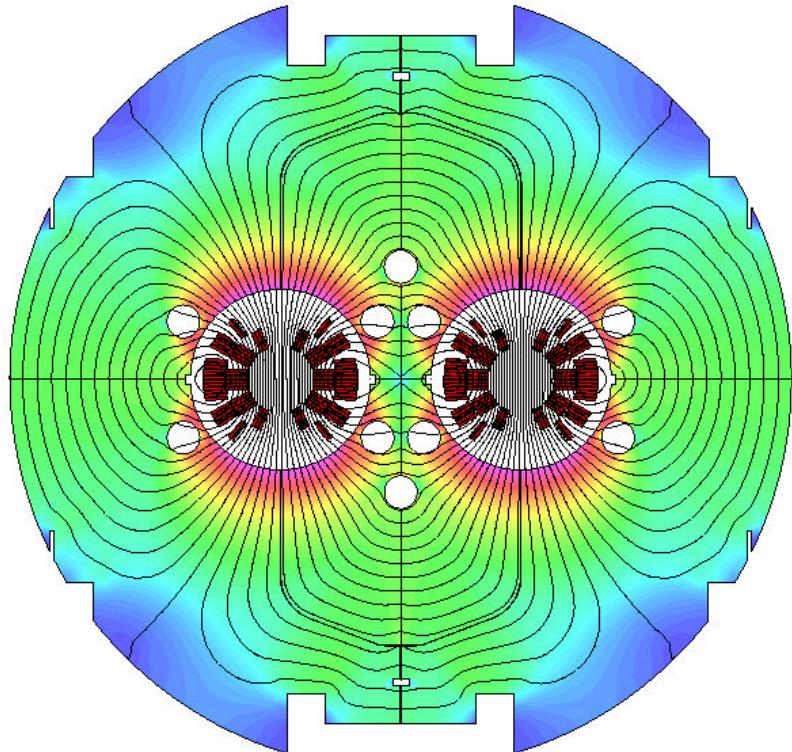


2-in-1 Cold Yoke Optimization



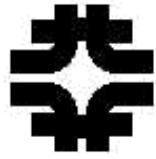


Double-Bore Cold-Yoke Design



Magnet parameters:

- bore diameter 43.5 mm
- bore separation 180 mm (160-200 mm)
- yoke OD 520 mm
- 3 pieces cold yoke with open vertical gap
- Al clamps and 10 mm thick SS skin
- correction holes



2-in-1 Warm Yoke Optimization

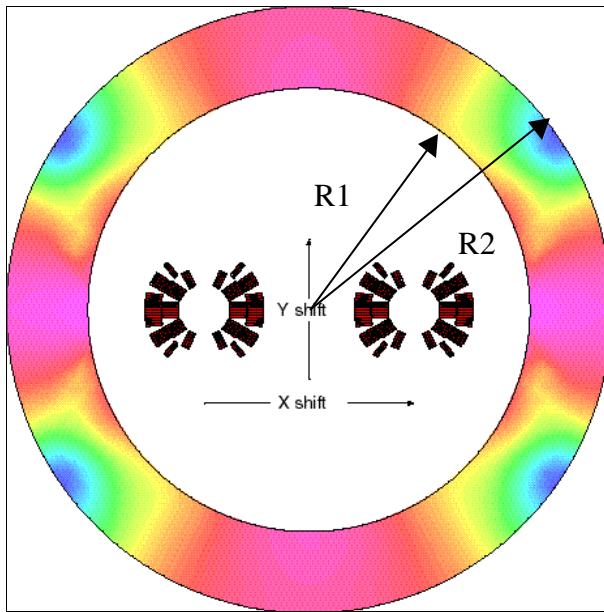
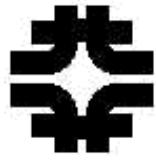


Table 1: Parameters of dipole magnets with “warm” and “cold” iron yoke

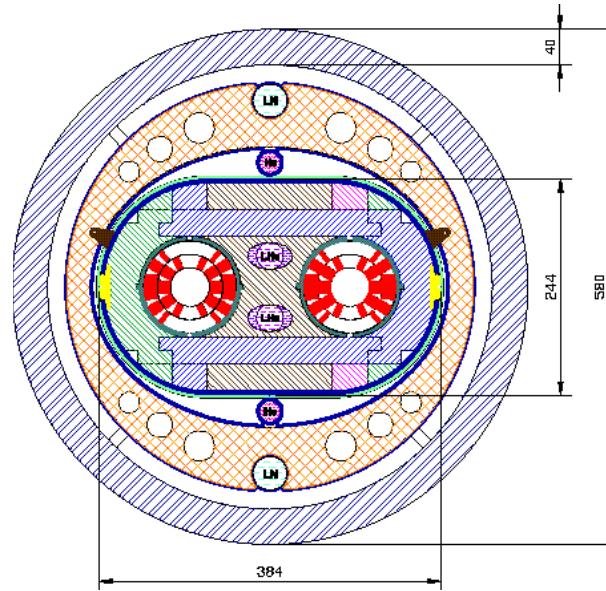
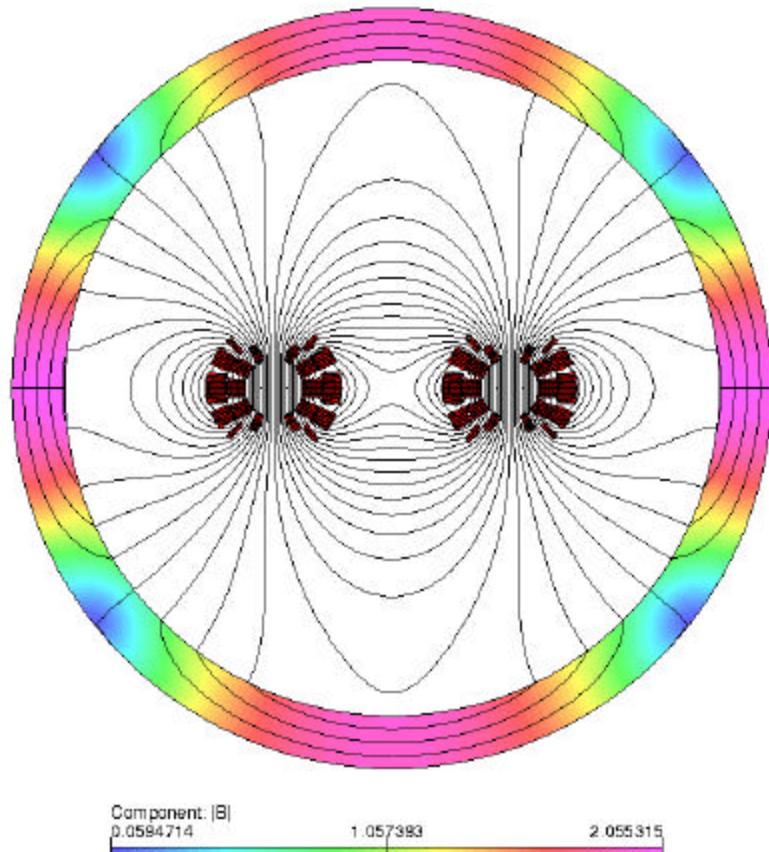
| R1, mm | R2, mm | Iron area, cm ² | I @11T, kA | Transfer function @11T, T/kA | Quench field, T (Jc=2000 A/mm ² @12T) | Bfr @11T, mT | Amplitude of multipole change in operation cycle, 10 ⁻⁴ |
|--|-----------|-------------------------------|---------------|---------------------------------------|--|--------------------|--|
| Warm iron yoke, double aperture magnet | | | | | | | |
| 190 | 260 | 989.6 | 22.85 | 0.481 | 11.4 | 28 | 1.24 0.07 |
| 250 | 290 | 678.6 | 23.41 | 0.470 | 11.3 | 22 | 0.64 0.02 |
| Cold iron yoke, double aperture magnet | | | | | | | |
| N/A | 260 | 1794.8 | 19.64 | 0.560 | 12.0 | 60 | 0.40 0.60 |

Table 2: Lorentz forces and multipole deviations due to coil/yoke misalignment

| R1, mm | R2, mm | Coil displacement | | Forces per coil block, kN/m | | Multipole deviations | | | | |
|-----------|-----------|----------------------|-----------------|-----------------------------------|--------------|----------------------|--------------|--------------|--------------|--------------|
| | | Δx , mm | Δy , mm | ΔF_x | ΔF_y | Δb_2 | Δb_3 | Δa_1 | Δa_2 | Δa_3 |
| 190 | 260 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | | 1.0 | 0.0 | 14.2 | 0.0 | 1.0 | -0.1 | 0.0 | 0.0 | 0.0 |
| | | 0.0 | 1.0 | 0.0 | 6.0 | 0.0 | 0.0 | 1.6 | -0.4 | 0.0 |
| 250 | 290 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | | 1.0 | 0.0 | 2.1 | 0.0 | 0.14 | 0.02 | 0.0 | 0.0 | 0.0 |
| | | 0.0 | 1.0 | 0.0 | 1.2 | 0.0 | 0.0 | 0.6 | -0.08 | 0.0 |

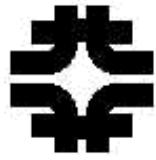


Double-Bore Warm-Yoke Design



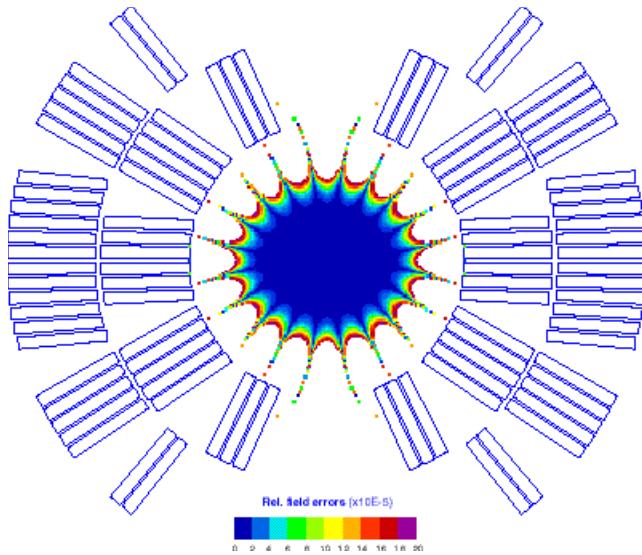
Magnet parameters:

- bore diameter 43.5 mm
- bore separation 180 mm (160-200 mm)
- cold mass size
- yoke OD 580 mm
- asymmetric coils

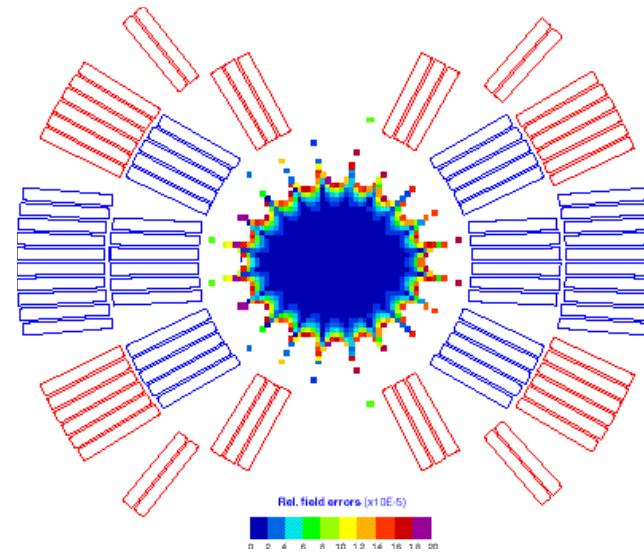


Compensation of b2 in Warm Iron Design

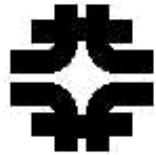
Symmetric block layout



Asymmetric block layout

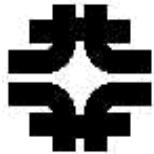


Block asymmetry less than 1 mm



Summary of Magnet Parameters

| Parameter | VLHC-S | VLHC-DC | VLHC-DW | LHC |
|---|--------------------|--------------------|--------------------|-----------|
| Superconductor | Nb ₃ Sn | Nb ₃ Sn | Nb ₃ Sn | NbTi |
| Nominal field, T | 11-12 | 11-12 | 10-11 | 8.4 |
| Operating temperature, K | 4.3 | 4.3 | 4.3 | 1.9 |
| Bore diameter, mm | 43.5 | 43.5 | 43.5 | 56 |
| Number of bores | single | double | double | double |
| Bore separation, mm | - | 150-200 | 150-200 | 194 |
| Coil design | cos-theta | cos-theta | cos-theta | cos-theta |
| Number of layers | 2 | 2 | 2 | 2 |
| Coil width, mm | 30 | 30 | 30 | 30 |
| Coil area, cm ² | 22.33 | 2x22.33 | 2x22.33 | 2x39.94 |
| Yoke design | cold | cold | warm | cold |
| Iron yoke OD, mm | 440 | 520 | 580 | 550 |
| Iron area, cm ² | 1370 | 1735 | 680 | ~2000 |
| Cryostat OD, mm | 650-700 | 750-800 | 580 | 914 |
| B/I @ B _{nom} , T/kA | 0.55 | 0.56 | 0.47 | 0.73 |
| Inductance @ B _{nom} , μH/m | 1.31 | 2x1.34 | 2x1.08 | 2x4.19 |
| Stored energy @ B _{nom} , kJ/m | 260 | 2x259 | 2x295 | 2x261 |

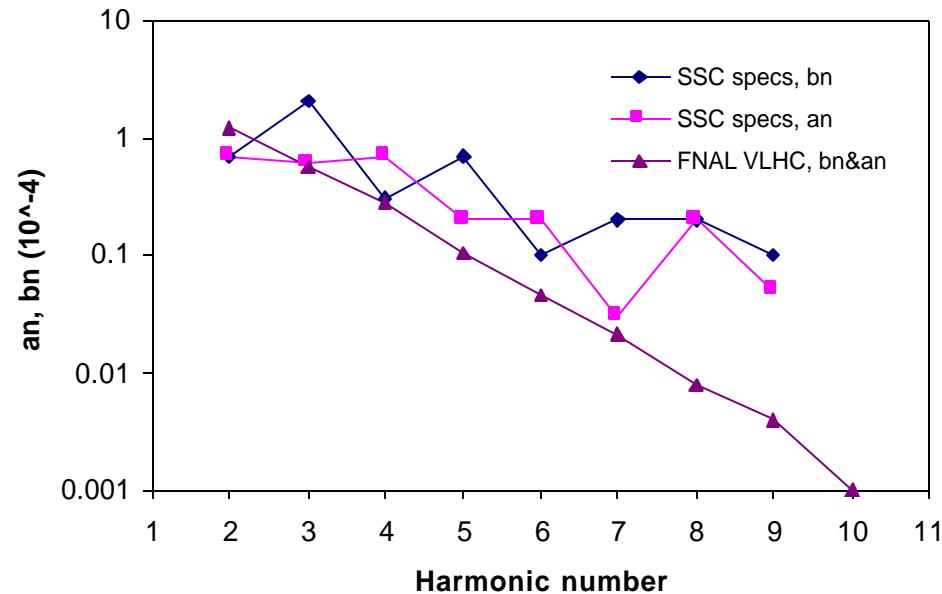


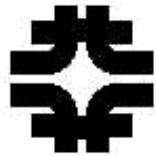
Field Quality

Systematic field errors @1 cm

| Field harmonics | b2 | b3 | b4 | b5 | b6 | b7 | b8 | b9 | b10 |
|-----------------|--------------|--------------|--------------|--------------|---------------|---------------|--------------|---------------|---------------|
| Symmetric coil | - | 0.000 | - | 0.000 | - | 0.000 | - | 0.071 | - |
| Asymmetric coil | 0.000 | 0.000 | 0.000 | 0.001 | -0.012 | -0.011 | 0.031 | -0.130 | -0.011 |
| SSC specs | - | 0.008 | - | 0.018 | - | 0.040 | - | 0.089 | - |

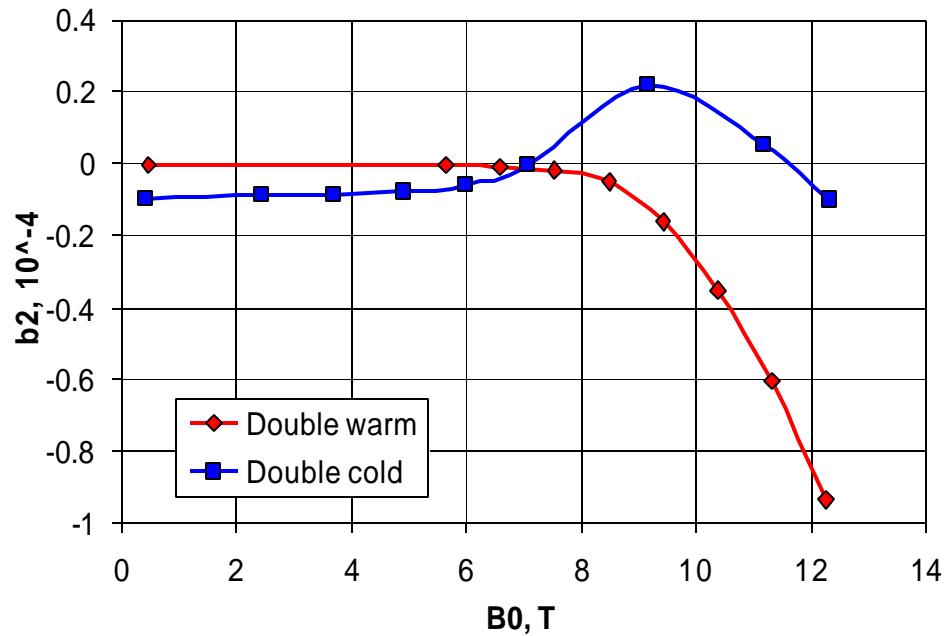
Random field errors @ 1 cm





Iron Saturation Effect

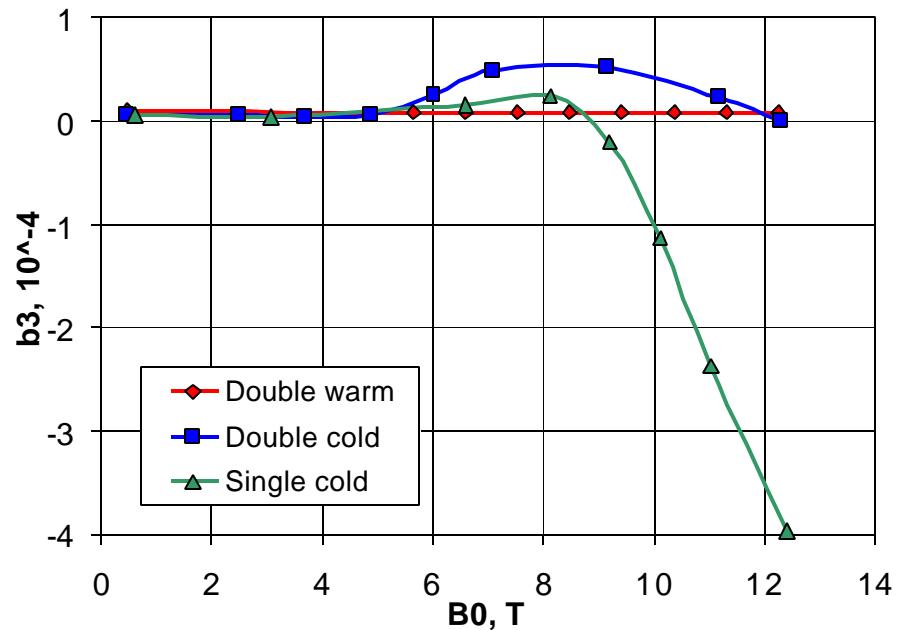
Quadrupole vs. bore field

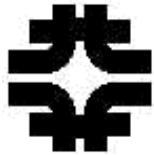


b2 correction:

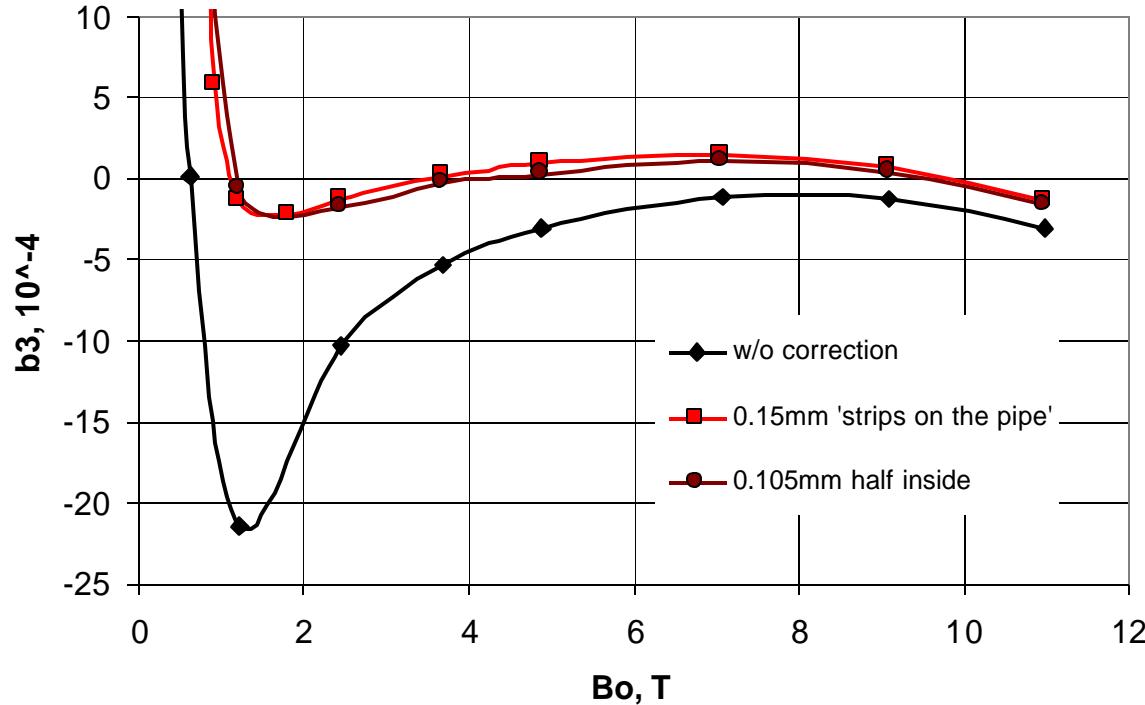
- cold yoke - holes
- warm yoke - asymmetric coil

Sextupole vs. bore field





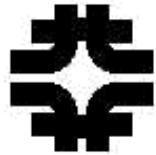
Coil Magnetization Effect



Persistent currents: small $d_{eff} < 40\mu m$, passive correction

Eddy current effects: - strand: small $l_p \sim 10-20$ mm
- cable: large R_a (cable with SS or iron core)

Snap-back effect: to be studied (measured!)



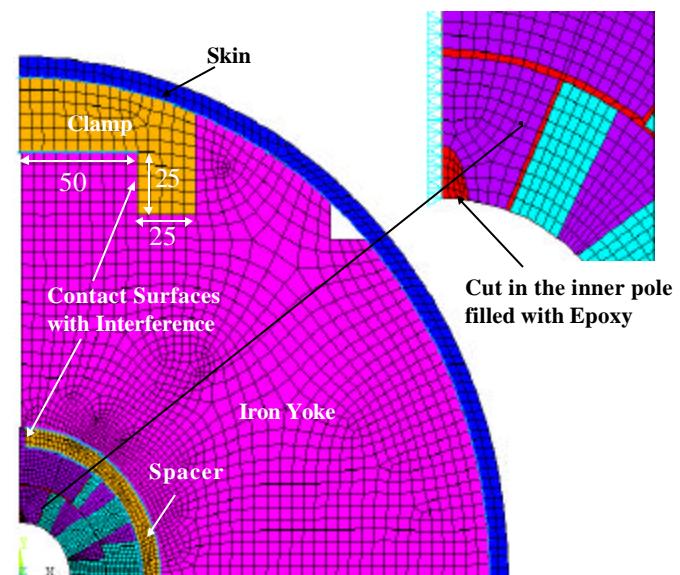
Mechanical Analysis

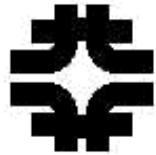
Peak equivalent stress in the coil (MPa)

| Design | 300K | 4.2 K, 0T | 4.2K, 12 T |
|-------------|------|-----------|------------|
| Single cold | 80 | 121 | 104 |
| Double cold | 120 | 132 | 125 |
| Double warm | 132 | 118 | 121 |

$\sigma_{az} > 0, \sigma_{eq} < 150 \text{ MPa} @ B < 12 \text{ T}$

Coil bore deformation: $\Delta R < 100 \mu\text{m}$

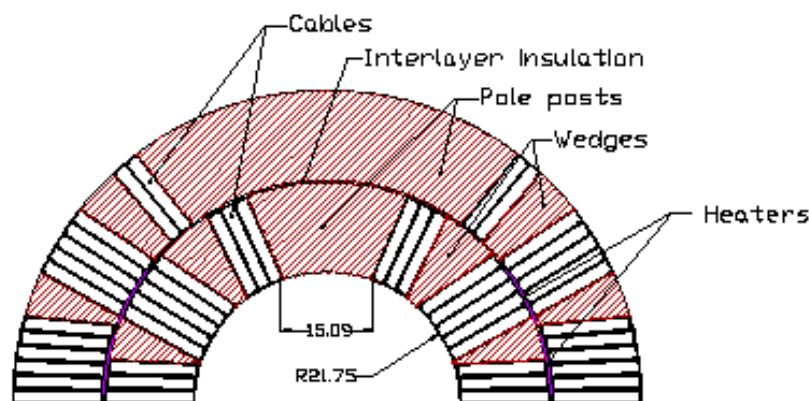




Quench Protection

Short model quench parameters

| | One heater | Two heaters |
|-----------------------|------------|-------------|
| Quench integral, MIIT | 12 | 10 |
| Tmax inner coil, K | 180 | 130 |
| Tmax outer coil, K | 130 | 100 |
| Vmax turn-turn, V | 15 | 18 |
| Vmax coil-ground, V | 100 | 110 |

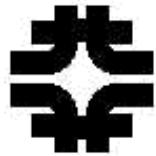


$$J_{cu} \sim 1.8-2.0 \text{ kA/mm}^2$$

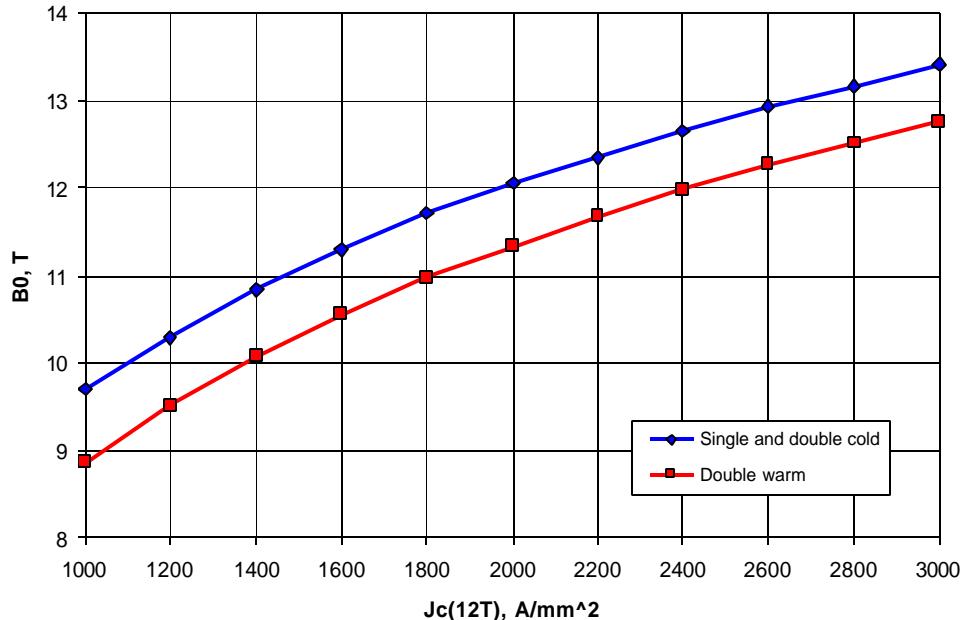
Min heater energy: ?

For long magnets

Cu:nonCu=1.2:1



Short Sample Limit & Nominal Field



Maximum field vs. $J_c@12T$ in the coil
Cu:nonCu=0.85:1

Critical current margin - 15%
Critical current degradation - 10%
Cu:nonCu ration - 1.2:1

$J_c(12T, 4.2K), kA/mm^2$

| |
|-----|
| 2.2 |
| 3.0 |

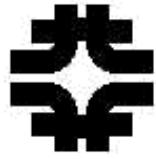
Cold yoke

| B_{nom}, T | B_{max}, T |
|--------------|--------------|
| 10 | 11.5 |
| 11 | 12.7 |

Warm yoke

| B_{nom}, T | B_{max}, T |
|--------------|--------------|
| 9.4 | 10.8 |
| 10.4 | 11.9 |

$$B_{nom} = 11-12(\text{cold yoke})/10-11 \text{ T(warm yoke)}$$



Summary

The designs of cos-theta dipole magnets for VLHC provide the maximum field of ~10-11 T using commercially available now Nb₃Sn strand.

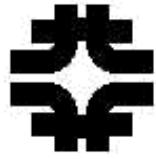
The nominal field of 11-12 T with sufficient (?) margin will be achieved using new R&D strands with $J_c(12T, 4.2K)=3kA/mm^2$.

Field quality in the field range of 1-12 T is quite good. Field range can be expended to the required value of 17 by reducing the effective filament size in R&D Nb₃Sn strands and using simple passive correction.

The chosen mechanical design and the coil prestress level provides the coil mechanical stability in the fields up to 11-12 T but safe for Nb₃Sn strand.

Magnet quench protection provided by the internal quench heaters keeps the coil quench parameters on the acceptable level. Some increase of the Cu content in full-scale coils is required.

Magnet parameters will be studied on series of short models. The fabrication of first single-bore model is underway. Tests are planned for the Fall of 2000.



Acknowledgments

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V. Kashikhin, P.J. Limon, A. Makarov, I. Terechkine, J.C. Tompkins,
S. Yadav, R. Yamada, V. Yarba, A. Zlobin, *FNAL, Batavia, IL, USA*
S. Caspi, R. Scanlan *LBNL, Berkeley, CA, USA*
M. Wake, *KEK, Tsukuba, Japan*

References:

1. V.V. Kashikhin, "First High Field Magnet Cross-Section Design", TD-99-027
2. G. Ambrosio et al., "Magnetic Design of the Fermilab 11 T Nb₃Sn Short Dipole Model ", *MT-16*, Tallahassee, FL, September 1999.
3. V.V. Kashikhin and A.V. Zlobin, "Conceptual Magnetic Design of the Fermilab 2-in-1 Nb₃Sn Dipole Magnet for VLHC", TD-00-008
4. V.V. Kashikhin and A.V. Zlobin, "Iron Yoke Optimization in the Double Aperture Nb₃Sn Dipole Magnet for VLHC", TD-00-009
5. V.V. Kashikhin and A.V. Zlobin, "Conceptual Design of the Double Aperture Nb₃Sn Dipole Magnet for VLHC with Warm Iron Yoke", TD-00-012
6. V.V. Kashikhin and A.V. Zlobin, "Compensation of Quadrupole Field Component in the VLHC Double Aperture Nb₃Sn Dipole Magnet with Warm Iron Yoke", TD-00-036